SPECTROSCOPY OF NEW SUBSTELLAR CANDIDATES IN THE PLEIADES: TOWARDS A SPECTRAL SEQUENCE FOR YOUNG BROWN DWARFS [1]

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[1]Based on observations made with the William Herschel Telescope, operated on the island of La Palma by the Royal Greenwich Observatory in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, and on data collected at the 3.5m telescope of Calar Alto German-Spanish Observatory.

ABSTRACT

We present optical and near-infrared spectroscopy (600–1000 nm) of eight faint (I>18) very red (R–I>2.2) objects discovered in a deep CCD survey of the Pleiades cluster (Zapatero-Osorio et al. 1996). We compare them with reliable cluster members like PPl 15 and Teide 1, and with several field very late-type dwarfs (M4–M9.5), which were observed with similar instrumental configurations.

Using pseudocontinuum ratios we classify the new substellar candidates in a spectral sequence defined with reference to field stars of known spectral types. We also reclassify PPl 15 and Teide 1 in a self-consistent way. The likelihood of membership for the new candidates is assesed via the study of their photospheric features, H_α emission, radial velocity, and consistency of their spectral types and I-band magnitudes with known cluster members. Four of the new substellar candidates are as late or later than PPl 15 (M6.5), but only one, namely Calar 3 (M8), clearly meets all our membership criteria. It is indeed an object very similar to the brown dwarf Teide 1.

Out of the eight new substellar candidates, our "cautious" membership analysis leaves only Calar 3 as a Pleiades brown dwarf with a high level of confidence. This object, together with Teide 1, allows one to compare the spectroscopic characteristics of Pleiades brown dwarfs with those of old very cool dwarfs. The overall spectral properties are similar, but there are slight differences in the NaI doublet (818.3 nm, 819.5 nm), VO molecular band (740 nm), and some spectral ratios, which are probably related to lower surface gravity in the young Pleiades brown dwarfs than in field stars. Finally, we propose a way of improving future CCD-based brown dwarf surveys by using narrow-band near-IR pseudocontinuum filters.

Subject headings: stars: low mass, brown dwarfs, spectroscopy – clusters: Pleiades

1. INTRODUCTION

The nearby ($\sim$ 125 pc) Pleiades open cluster is now widely recognized as one of the best places in the Galaxy to identify free-floating brown dwarfs (BDs). Its young age (70–130 Myr) implies that BDs should be caught at a relatively hot and luminous stage of their lives. Several groups have recognized the advantages of BD searches in this cluster, and consequently a number of photometric surveys have been reported (see Jameson 1995 for a review). The masses of photometric candidates can in principle be estimated from their position in the H-R diagram and comparison with theoretical evolutionary tracks. However, uncertainties in the conversion of photometric data to stellar parameters (T_{eff}, Luminosity), and in the accuracy of model predictions have for many years prevented reaching a definitive conclusion regarding the substellar status of the best BD candidates found in the different surveys. The presumption of substellar mass for free-floating objects cannot be tested dynamically. Nevertheless, it can be inferred from the spectroscopic test, sometimes called the Li-test, proposed by Rebolo, Martín & Magazzù (1992). The first applications of the Li-test to BD candidates in binary systems, the field and in open clusters gave only Li non-detections (see Rebolo, Magazzù & Martín 1995) for a review. But very recently, the first positive detections have been announced in the Pleiades objects PPl 15 (Basri, Marcy & Graham 1996) and Teide 1 (Rebolo et al. 1996). The presence of Li in these two faint ($I \geq 17.8$) Pleiades members, and its absence in slightly more luminous stars implies that the stellar-substellar borderline in the cluster has been crossed.

Eight new Pleiades BD candidates with $I>18$ have been identified as very red ($R–I>2.2$) objects in deep CCD images obtained by Zapatero-Osorio, Rebolo & Martín (1996). These objects will be referred throughout this paper with the abridged names given by Zapatero-Osorio et al, which are based on their I-band apparent magnitudes and the observatories where they were first observed. Follow-up spectroscopic observations are essential in order to assess the cluster membership and improve our knowledge of the atmospheres of Pleiades brown dwarfs. In this paper we present optical and near-infrared spectra of all the BD candidates discovered by Zapatero-Osorio et al. (1996). We have obtained spectral types, luminosity classes, radial velocities and H_{α} emission equivalent widths. Based on all such information we conclude that one of the Calar objects is very similar to the brown dwarf Teide 1. We

use our enlarged battery of standards for revising the spectral type determination of PPl 15 and Teide 1, and for discussing the differences between the spectroscopic properties of young brown dwarfs and main sequence stars.

2. OBSERVATIONS

The observations for this programme were carried out on the 4.2 m William Herschel Telescope (WHT), located at the Observatory del Roque de los Muchachos, and on the 3.5 m telescope of Calar Alto Observatory. The observing log is shown in Table 1, and we have added observations of PPl 1, Teide 1 and LHS 2065 obtained in previous runs (Martín 1993; Rebolo, Zapatero-Osorio & Martín 1995) with similar instrumental setups. The targets are grouped in two groups (Pleiades and field) and ranged alphabetically. The apparent I-magnitudes come from Bessell (1991) and Leggett (1992) for the field stars, and Stauffer, Hamilton & Probst (1994), and Zapatero-Osorio et al. (1996) for the Pleiades objects. All of them are in the Cousins-Kron photometric system. The instrumentation used was the ISIS double arm spectrograph at the WHT, and the twin spectrograph at Calar Alto. In both telescopes we removed the dichroic and used the red arm only. We kept the same configuration throughout the runs, namely: grating R158R + TEK (1124x1124) chip (WHT) and grating No. 11 + TEK (1124x1124) chip (3.5 m Calar). The spectral resolution and coverage obtained with each instrument were 5.8 Å (R$\sim$1200) and 612.6–907.0 nm; 7.8 Å (R$\sim$950) and 635.0–1025.0 nm, respectively.

The weather conditions in both (WHT and Calar Alto) runs were severely hampered by clouds. Sometimes a long exposure had to be paused or cut off because the star used for autoguiding became invisible. Seeing was highly variable, ranging from 4 arcsec to less than 1 arcsec. In the last column of Table 1 we have marked those observations where we noticed passing clouds.

Each individual spectrum was reduced by a standard procedure using IRAF[2], which included debias, flat field, optimal extraction and wavelength calibration using arc lamps. The rms of the wavelength calibration was always better that 1/10 of a pixel. Finally, the spectra were flux calibrated using the standard HD 19445, which has

[2]IRAF is distributed by the National Optical Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

Table 1: Log of spectroscopic observations

Name	I	Tel.	t_{exp}	No. exp	Date	Weather
Calar 1	18.2	3.5 m	5400	2	Oct 27, 1995	clear
		WHT	9400	3	Oct 29, 1995	clear
Calar 2	18.7	3.5 m	7200	3	Oct 27-29, 1995	cloudy
Calar 3	18.7	3.5 m	16200	5	Oct 28-29, 1995	clear
		WHT	2320	1	Oct 30, 1995	cloudy
Calar 4	18.9	3.5 m	5400	2	Oct 28, 1995	clear
		WHT	5450	2	Oct 29, 1995	cloudy
Calar 5	19.0	3.5 m	10200	4	Oct 28-29, 1995	cloudy
Calar 6	19.2	WHT	6800	2	Oct 30, 1995	clear
Calar 7	19.7	WHT	6800	2	Oct 30, 1995	clear
PPl 1	17.5	INT	3600	2	Jan 23, 1992	clear
PPl 14	17.4	WHT	1800	1	Oct 29, 1995	clear
PPl 15	17.8	WHT	3600	3	Oct 29, 1995	clear
Roque 1	18.4	WHT	9000	3	Feb 17, 1996	clear
Teide 1	18.8	WHT	16600	7	Dec 29-30, 1994	clear
BRI 0021-0214	15.1	3.5 m	1200	1	Oct 27, 1995	clear
		WHT	4000	3	Oct 28-29, 1995	cloudy
GJ 51	10.4	3.5 m	30	1	Oct 29, 1995	clear
		WHT	480	1	Oct 28, 1995	cloudy
GJ 65 AB	8.3	WHT	400	1	Oct 28, 1995	cloudy
GJ 83.1	9.2	WHT	300	1	Oct 28, 1995	cloudy
GJ 402	8.9	3.5 m	30	1	Oct 30, 1995	cloudy
GJ 873	7.6	3.5 m	25	2	Oct 29, 1995	clear
GJ 905	8.8	3.5 m	80	2	Oct 29, 1995	clear
LHS 248	10.5	3.5 m	50	2	Oct 30, 1995	cloudy
		WHT	400	2	Oct 30, 1995	clear
LHS 2065	14.5	WHT	600	1	Dec 30, 1994	clear
LP 412-31	15.0	3.5 m	1000	1	Oct 28, 1995	clear
PC 0025+0447	18.5	3.5 m	5400	2	Oct 29, 1995	clear
VB10	12.8	3.5 m	1200	1	Oct 28, 1995	cloudy
		WHT	900	2	Oct 28, 1995	clear

Notes: GJ 65 A and B were not resolved on the slit due to poor seeing. The acronyms for the telescopes stand for 2.5 m Isaac Newton telescope (INT), 4.2 m William Herschel

absolute flux data available in the IRAF environment. In Figure 1 we present the final spectra of BD candidates observed with the WHT, together with PPl 14, PPl 15, Teide 1 and three M5–M9 V standards. The spectra were ordered by increasingly late spectral type. In Figure 2 we show spectra obtained with the 3.5 m Calar Alto telescope. The Isaac Newton telescope spectrum of PPl 1 has a resolution of 5.8 Å, similar to the WHT spectra, but it is quite noisy.

3. ANALYSIS

The main photospheric features of very late type dwarfs that can be studied with low resolution optical-NIR spectra are the molecular bands of CaH, TiO and VO, and the strong atomic lines of NaI and KI. In principle they can provide us information about basic atmospheric properties like luminosity, metallicity and temperature. We expect that cluster stars share the same age and metallicity, and thus they provide a homogeneus sample for learning about how the atmospheres change towards lower masses. We can also learn about the problem of chromospheres by measuring the strength of H_α in emission. In this section we start presenting our method for quantitatively measuring spectral types, which is based on flux ratios. There is a good correlation between spectral type (in the range M4–M9.5) and some (but not all) flux ratios. We proceed by assigning spectral types to the objects found towards the Pleiades, and we also derive the strengths of photospheric features, H_α and radial velocities.

3.1 Pseudocontinuum spectral ratios

The overall optical-NIR spectrum of very cool stars is largely depressed by molecular opacity. The true stellar continuum is never seen, but at a few points the molecules are a little more transparent and one sees deeper in the photosphere, forming a pseudocontinuum (PC hereafter). In our spectral range this happens around wavelengths 653.9, 704.5, 756.0, 824.5, 884.0, 920.0 and 985.0 nm.

Strong telluric bands (i.e. more than 10% absorption) are present in the following regions: 685.8–703.2, 715.3–737.7, 757.7–769.2, 809.9–834.5, 892.0–965.0 and 984.0–1012.0 nm. We cancelled out the bulk of the telluric absorption using the flux standard HD 19445 (G metal poor star) observed with the same instrumental setting as the programme stars.

Table 2: Pseudocontinuum Integration Limits (nm)

PC index	Numerator	Denominator
PC1	703.0–705.0	652.5–655.0
PC2	754.0–758.0	703.0–705.0
PC3	823.5–826.5	754.0–758.0
PC4	919.0–922.5	754.0–758.0
PC5	980.0–988.0	754.0–758.0

Previous works have pointed out that PC ratios are well correlated with M spectral subclass (Martín 1993, Hamilton & Stauffer 1993). We have defined five PC indices, as ratios between the average flux at two different spectral regions. In Table 2 we specify the integration limits that we have used, and in Table 3 we give the values measured in dwarfs of known spectral type from Kirkpatrick, Henry & Simons (1995). All the stars were corrected for their intrinsic doppler velocity prior to calculating the ratios.

The PC1 and PC2 ratios have similar behavior: they increase with increasingly late spectral type until ∼ M8 and decrease afterwards. This “saturation” effect has also been noticed in the (R–I) color by Bessell (1991). The double-values of PC1 and PC2 make them unreliable for spectral type classification, and hence we do not use them for that purpose. The other three indices do not present such saturation, as they do increase monotonically up to M9.5. Their dependence with spectral type can be well fitted by second order polynomials giving the following relationships:

$$SpT = -8.009 + 14.080 \times PC3 - 2.810 \times PC3^2 \quad N = 11 \quad \sigma = 0.39$$

$$SpT = -0.944 + 4.663 \times PC4 - 0.515 \times PC4^2 \quad N = 8 \quad \sigma = 0.22$$

$$SpT = 1.038 + 2.979 \times PC5 - 0.264 \times PC5^2 \quad N = 7 \quad \sigma = 0.32$$

where SpT is the M subclass number, N is the number of data points, and σ is the standard deviation in spectral type subclass of the polynomial fit to the PC values.

Table 3: PC measurements for field dwarfs

Name	SpT.	PC1	PC2	PC3	PC4	PC5
GJ 873	M3.5 V	1.31	1.40	1.12	1.18	1.08
GJ 402	M4 V	1.44	1.47	1.12	1.21	1.15
GJ 83.1	M4.5 V	1.40	1.50	1.13		
GJ 51	M5 V	1.44	1.67	1.13		
GJ 905	M5.5 V	1.66	1.74	1.26	1.54	1.47
GJ 65 AB	M5.5 V	1.56	1.91	1.29		
LHS 248	M6.5 V	1.82	2.10	1.45	2.12	2.22
VB10	M8 V	2.20	2.43	1.82	2.79	3.41
LP412-31	M8 V	2.13	2.51	1.84	2.79	3.44
LHS 2065	M9 V	1.60	1.94	1.91		
PC 0025+0447	M9.5 V	1.87:	1.76:	2.11	3.91	6.75:
BRI 0021-0214	M9.5 V	2.09	1.88	2.42	4.11	5.86

Notes: The average error bar for the PC indices is ± 0.1, except for the values marked with a colon, which have a factor of 2 larger uncertainty. The PC4 and PC5 indices could not be measured in the WHT spectra because they have shorter spectral range than the Calar Alto spectra. The spectral types were taken from Kirkpatrick et al. (1995).

3.2 Spectral types for Pleiades objects

We have used the PC ratios measured in stars of known spectral type to calibrate them. Thus, we can apply the relationships given above to derive spectral types for new objects. Unfortunately, we could not measure the PC4 and PC5 indices in our WHT spectra as they do not go far enough into the red. The only exception is Roque 1, which was observed at the WHT but the spectral range does include the PC4 index. We note that for Teide 1, our spectral type is solely based on the PC3 index. Rebolo et al. (1995) estimated M8.5–M9 from two different calibrations, which is consistent within the uncertainties with the spectral type derived in this work.

For those objects observed at Calar Alto we took the average M subclass obtained from the PC3, PC4 and PC5 values. The 1σ dispersion was typically 0.3 spectral subclasses. Thus, we estimate that the spectral types given in Table 3 are safe to better than half a spectral subclass. In Table 4 we give the PC ratios measured in the Pleiades objects, and the spectral types that we infer from them. In Figure 3 we plot the PC2 and PC3 indices versus spectral type for the programme stars. Different symbols are used to distinguish the Pleiades objects from the field dwarfs. We have plotted these two ratios to illustrate how one (PC2) is not a good indicator of spectral type in the range M5–M10, whereas the other (PC3) is indeed a good indicator in the same range.

3.3 Absorption Features

The main molecular bands in the optical-NIR spectrum of our programme stars are due to CaH, TiO and VO. Kirkpatrick et al. (1991) defined the A-index for measuring the strength of CaH at 675–705 nm. In Table 5 the A-index measured in our spectra are brought together with the VO-index of Kirkpatrick et al. (1995) and the TiO-index of Martín & Kun (1996).

The strongest atomic lines in our spectral range are the NaI doublet at 818.3 and 819.5 nm, and the KI resonance doublet at 766.5 and 769.9 nm. In Table 5 we give the equivalent widths (EW) of these atomic lines, which were obtained by direct integration of the two lines (partially blended in our spectra). The continuum levels for the EWs of the KI and NaI doublets were set at the average flux in 30 Å around 764.5 and 814.0 nm, respectively. Note that these are not the true continuum for the absorption lines, but the observed pseudocontinuum. Our EW values should be considered as lower

Table 4: PC measurements and spectral types for Pleiades objects

Name	SpT.	PC1	PC2	PC3	PC4	PC5
Calar 7	M4	1.35	1.71	1.12		
Calar 4	M5	1.46	1.68	1.29	1.22	1.33:
PPl 14	M5.5	1.71	1.95	1.27		
Calar 6	M5.5	1.51	2.04	1.30		
Calar 2	M6	1.74:	1.88:	1.41	1.70	2.17::
PPl 15	M6.5	1.63	2.20	1.44		
PPl 1	M6.5	1.82::	2.77::	1.46:		
Calar 5	M6.5	1.51:	2.04	1.52	1.86	2.27:
Roque 1	M7	1.50	2.21	1.60	2.38	
Teide 1	M8	2.25	2.65	1.73		
Calar 3	M8	2.36	2.84	1.77	2.84	3.17:
Calar 1	M9	2.84	2.21	1.99	3.31	4.20:

Notes: The average error bar for the PC indices is ± 0.1, except for the values marked with one or two colons, which have factors of 2 and 3 larger uncertainty, respectively. The PC4 and PC5 indices could not be measured in the WHT spectra because they have shorter spectral range than the Calar Alto spectra. The uncertainty in spectral type is half a spectral subclass.

Table 5: Absorption Features

Object	A	TiO	VO	KI (Å)	NaI (Å)
GJ 873	1.33	1.47	1.00	11.7	3.2
GJ 402	1.29	1.56	1.00	10.6	3.9
GJ83.1	1.40	1.66	1.00	11.5	6.1
GJ 51	1.41	1.77	1.00	11.9	6.0
GJ 905	1.32	1.81	1.02	18.1	5.7
GJ 65 AB	1.50	1.92	1.02	15.6	6.6
LHS 248	1.57	2.15	1.05	28.3	7.4
VB10	1.42	1.70	1.12	18.0	6.3
LP412-31	1.53	1.63	1.12	17.2	7.4
LHS 2065	1.24	1.26	1.13	9.5	4.7
PC 0025+0447	1.21	0.61	1.17	10:	2::
BRI 0021-0214	1.35	1.02	1.11	16.2	3.9
Calar 7	1.30:	1.47:	1.02	14::	5.6:
Calar 4	1.36:	1.67:	1.00	11:	3.5::
PPl 14	1.33	2.03	1.04	22.8:	5.8
Calar 6	1.40:	1.77:	1.01	21.3:	6.5
Calar 2	1.36::	2.99::	1.04	20.2:	7.2
PPl 15	1.51	2.26	1.06	21.0:	4.8
PPl 1	1.14::	2.47::	1.01::	20::	8.8::
Calar 5	2.98::	1.63:	1.05	21.3:	5.2:
Roque 1	1.89	2.50:	1.03	23.5:	8.9
Teide 1	1.48	1.55	1.15	16.8:	5.1
Calar 3	1.20:	1.58:	1.16	20.2:	4.5:
Calar 1	1.40	1.44	1.07	30::	6.6

Notes: The error bars are ±0.5 and 1 Å for the NaI and KI EWs, respectively, and 5% for the indices, except for the values marked with one or two colons, which have factors of 2 or 3 larger uncertainty.

limits to the true equivalent widths.

The NaI doublet and the KI line at 766.5 nm are affected by telluric bands which absorb up to 15% of the continuum. We have estimated that if we had not corrected from telluric absorption our EWs of the NaI doublet would be larger by $\sim$10% . Note for instance that the C-index of Kirkpatrick et al. (1991), which measures the NaI doublet, was not corrected for telluric absorption, and their published values should be decreased by about 10% . We find a good agreement for the stars in common after allowing for this correction. The effect of telluric absorption on the KI doublet is more dramatic, and we find in general that the EWs are a factor of $\sim$2 larger after correction. The NaI doublet in some spectra from Calar Alto are affected by one bad pixel in the detector. We substituted the bad pixel by the interpolated value of the two adjacent ones.

3.4 H_α Emission and Radial Velocities

We derived the H_α EW in our spectra via direct integration of the line profile. The results are given in Table 6. We give the measurements of individual exposures when H_α was variable. For Teide 1 the average H_α EW of seven spectra is 6 Å (Rebolo et al. 1995). In Table 6 we give the H_α EWs for the three best individual spectra (each 1 hour integration time at the WHT). We have noted significant H_α variability in LHS 248, VB10, PC 0025+0447 and Teide 1.

Radial velocities were computed via cross-correlation of the spectra with templates of similar spectral type. We used as templates LHS 248 (Basri & Marcy 1995), VB10 (Goldberg 1995), and BRI 0021-0214 (Basri & Marcy 1995). For LHS 2065 and Teide 1 we adopted the radial velocities given by Martín, Rebolo & Magazzù (1994) and Rebolo et al. (1995), respectively. The radial velocities obtained for the programme stars and the reference star used are given in Table 6. The spectral window selected for the cross correlation was 840–880 nm, which is free for telluric bands and contains a lot of photospheric lines in late-type spectra (Mazeh et al. 1996).

The velocity dispersion of our spectra is rather poor for radial velocity work (137.5 km $s^{-1}pix^{-1}$ at Calar, and 116 km $s^{-1}pix^{-1}$ at the WHT). Nevertheless, the cross correlation technique was able to achieve precisions of about 1/4 of a pixel, so we obtained radial velocities accurate to about 30 km s^{-1}. We verified this by cross

Table 6: H_α Emission and Radial Velocities

Object	JD –2400000	H_α (Å)	Vrad (km s^{-1})	Template
GJ 65 AB	50020.78	8.2	62	LHS 248
LHS 248	50020.65	3.3	9*	
	50020.77	5.5		
VB10	50019.35	2.9	35*	
	50019.37	6.3		
LP412-31	50018.68	28.6	1	VB10
LHS 2065	49716.56	10.7	4.5*	
PC 0025+0447	50020.38	475	46	BRI 0021-0214
	50020.40	366	20	BRI 0021-0214
BRI 0021-0214	50018.06	<0.4	13*	
	50019.49	<0.1		
Calar 7	50020.70	<0.5	-109:	LHS 248
Calar 4	50020.56	<2.5		
PPl 14	50019.52	3.7	22:	LHS 248
Calar 6	50020.70	<0.5	-62	LHS 248
Calar 2	50020.56	<1.5	-5:	LHS 248
PPl 15	50020.61	11.5:	20	LHS 248
PPl 1	48645.43	6.5:	14*	
Calar 5	50020.61	6.5	-8:	LHS 248
Roque 1	50131.49	≤1.5	151	LHS 248
Teide 1	49716.41	3.5:	2*	
	49716.46	3.7:		
	49716.50	8.6		
Calar 3	50020.51	10.2	-14	VB10
Calar 1	50019.65	≤2.5	85	VB10

Notes: The average error bars are ±1.0 Å for the equivalent widths, and 30 km $s^{-1}$for the radial velocities, except where marked with colons, which have error bars a factor of 2 larger. The asterisks denote radial velocities taken from the literature (see text). The spectra of Calar 4 and PPl 1 were too noisy for deriving a radial velocity.

correlating the standards against each other. The main limitation on the radial velocity accuracy comes from the broadness of the cross-correlation peak due to the shape of the molecular absorption bandheads. It is also possible that part of the error comes from mismatches between the target and the template. We correlated every target with its closest proxy in spectral type. For Calar 4 and PPl 1 the cross-correlation peaks were too broad and asymmetric and we could not derive radial velocities for them. The radial velocity of PPl 1 has been measured by Stauffer et al. (1994b), and that is the value quoted in Table 6.

4. DISCUSSION

4.1 Cluster Membership

The key question about the nature of our eight new BD candidates is whether they belong to the Pleiades. Photometrically they occupy the region of the (R–I) vs I diagram where substellar cluster members are expected to be located (Zapatero-Osorio et al. 1996). However, this is not a strong enough constraint as other types of objects could have similar photometric properties (reddened galaxies, background red giants and late-type dwarfs, foreground very late-type dwarfs). In this section we use the analysis of the spectroscopic data described above to asess the membership status of each Calar object and Roque 1. We compare them with bona fide very low mass cluster members, and in particular PPl 15 and Teide 1. Our approach has been "cautious" in the sense that we retained as members only the objects that fully meet all the criteria (gravity, radial velocity, H_α , spectral sequence). Thus, we may have left out possible members rather than to accept field stars as members.

First, we look at the gravities. An interesting piece of information is the fact that all the Pleiades BD candidates present KI and NaI photospheric features (Section 3.2), implying that they are dwarfs (cf. Kirkpatrick et al. 1991). None of them is a red giant or an extragalactic object. This result indicates that the region of BDs in the I-band vs. (R–I)-color diagramme of the Pleiades cluster is not significantly contaminated by giants and extragalactic objects.

A kinematic constraint on membership comes from the fact that isolated brown dwarfs are thought to be formed as independent condensations in a manner similar to low mass stars, and hence they should also share the bulk motion of the cluster. The radial

velocities of known members of the Pleiades are in the range 0–14 km s^{-1} (Stauffer et al. 1994b). Taking into account the radial velocities given in Table 6 and their error bars, we consider as possible kinematical members Calar 2, 3 and 5. The other objects could be field stars, or large-amplitude spectroscopic binaries, or even run-away objects. However, from a "cautious" point of view we just consider them as kinematical non-members in the third column of Table 7.

Another criterion of membership in the Pleiades is the presence of H_α in emission. Hodgkin, Jameson & Steele (1996) measured the H_α strength of 6 proper motion members with I magnitude ≥ 16.5. All of them had H_α emission with equivalent widths in the range 3.1–6.8 Å. Stauffer et al. (1994a,b) found a similar range of H_α equivalent widths among their Pleiades PPl stars. We find that PPl 1, PPl 14, PPl 15 and Teide 1 show similarly strong H_α lines (Table 6). However, among field very late type stars, there are many cases of weak H_α emission. For instance Martín et al. (1994) found H_α EW less than 3 Å for 5 out of 10 M7–M9 field dwarfs. To summarize, we consider that H_α emission equivalent width < 3 Å indicates that an object of spectral type in the range M4–M8 is probably not a Pleiades member. The value of 3 Å is somewhat arbitrary, but it reflects the lower envelope of the H_α equivalent widths measured among Pleiades very low mass objects. We have to make an exception with Calar 1 as it has the latest spectral type known in a dwarf towards the Pleiades cluster. We do not know what to expect for H_α in objects cooler than Teide 1, and therefore this criterion cannot be applied for Calar 1.

Usually cluster members are expected to follow a tight sequence in the H-R diagram. PPl 15 and Teide 1 extend the Pleiades sequence towards magnitudes as faint as the new BD candidates. This is illustrated in Figure 4 where we display apparent I-magnitudes versus spectral types. We have plotted the proper motion members (HHJ stars) with spectral types later than M4 (determined by Martín et al. 1994 for HHJ 10, and Steele & Jameson 1995 for the rest), three PPl objects and Teide 1. A spectral sequence is clearly defined by these objects. We have also plotted the new BD candidates using different symbols for clarity. Only Calar 3 and Roque 1 nicely fit with the spectral sequence. Calar 3 is indeed very close to Teide 1. The rest of the Calar objects lie below the sequence, except Calar 1. We note that one of the HHJ stars is also well below the sequence.

Table 7: Membership Status

Object	Gravity	Vrad	H_α	Sp.Seq.	Final
Calar 1	Yes	No	?	Yes?	No
Calar 2	Yes	Yes	No	No?	No?
Calar 3	Yes	Yes	Yes	Yes	Yes
Calar 4	Yes	?	No	No	No
Calar 5	Yes	Yes	Yes	No?	No?
Calar 6	Yes	No	No	No	No
Calar 7	Yes	No	No	No	No
Roque 1	Yes	No	No	Yes	No

There is some controversy about a possible age spread in the Pleiades cluster (e.g. Stauffer et al. 1994). This issue is not yet settled, and in fact it could partially explain the spread seen in Figure 4. Very low mass Pleiades objects are gravitationally contracting and hence their luminosity and temperature are time-dependent. We have used a grid of evolutionary tracks kindly provided by F. D'Antona with a time step of 10 Myr in the mass range 0.1–0.06 $M_\odot$ to estimate the change in I-band magnitude due to a possible range of ages of 70–130 Myr among Pleiades objects. We have obtained a maximum difference in I-band of ~ 0.7 mag (shown in Figure 4 as a vertical dotted line). In fact, among the M5.5 and M6.5 Pleiades members the spread in I-band magnitudes seems similar to that expected for a 60 Myr age spread. Such an age spread may not be real, but so far it cannot be ruled out. BD candidates like Calar 1, 2 and 5 could be consistent with the spectral sequence if there is such an age spread and taking into account the error bars of ~ 0.1 mag in I-band and half a spectral subclass in spectral type. Moreover, Zapatero-Osorio et al. (1996) have shown that Calar 2 and 5 are affected by abnormal reddening probably due to a small interstellar cloud. The de-reddening correction is about 0.5 magnitudes in the I-band. Thus, we cannot rule out that these objects are cluster members just from Fig. 4.

Our "cautious" conclusions regarding membership for the objects are given in the sixth column of Table 7. We see that there are some clear-cut cases where all membership criteria agree. For instance Calar 6 and 7 have spectral types and radial velocities

inconsistent with membership, and moreover H_α emission is not detected, so they are obvious non-members. On the other hand, Calar 3 is the only object for which all the criteria are affirmative so it is very likely a cluster member. However, there are also ambigous cases where the criteria disagree. We discuss them individually:

Calar 1: It is the coolest dwarf found in our survey (M9). However, it appears to be too bright for its spectral type in Figure 4, and it has too high a radial velocity. If it is a binary with almost equal mass components, it would be overluminous and if the orbital period is short its radial velocity would be variable. However, our spectra do not show any hint for radial velocity variability, nor the presence of line splitting. Tentatively, we consider this object as a non-member for further discussion in this paper, but it is certainly worth to check if it is a spectroscopic binary. Zapaterio-Osorio et al. (1996) estimated that the probability of finding an M9 field dwarf in their survey is only $\sim 10\%$ on the basis of the density of M9 dwarfs in the solar neighbourhood. However, we note that the high radial velocity of Calar 1 is more typical of an old disk star than of a young disk star. It may be that the contribution of old disk M9 dwarfs starts to become significant in a survey like that of Zapatero-Osorio et al. which goes much deeper than larger-area surveys in the solar neighbourhood. Alternatively, Calar 1 may have been born in an unstable triple system, and has been ejected from it by interaction with more massive companions. In any case, this object is one of the few M9 dwarfs known in the whole sky, and deserves further investigation.

Calar 2: A dwarf with radial velocity consistent with membership. However, given our large error bar on the radial velocity this is a weak constraint. We give more weight to the fact that lies out of the spectral sequence of Figure 4 (although marginally consistent within the uncertainties), and it does not show H_α in emission. Thus, we consider that this object is more likely a background old dwarf than a cluster member, but we cannot reach a definitive conclusion with our data.

Calar 5: Its gravity, radial velocity and H_α are all supportive of membership, but it does not fit the spectral sequence. As mentioned before, Calar 5 is affected by larger reddening than the average in the Pleiades cluster, probably due to a small interstellar cloud (Zapatero-Osorio et al. 1996). However, the de-reddening correction is not enough to put it in the region of Pleiades members in Figure 4. This casts serious doubts on its

membership. Together with Calar 2, Calar 5 would need more data (proper motion, accurate radial velocity) in order to finally establish whether or not it belongs to the cluster. Interestingly, there is one proper motion member (HHJ 7) which lies in the same region of Figure 4 as Calar 2 and 5. HHJ 7 has weak H_α emission (Hodgkin et al. 1996) and according to our membership criteria we would consider it as a probable cluster non-member. However, if future observations establish that HHJ 7, Calar 2 and 5 have radial velocities and proper motions consistent with membership, the important implication would be that there is a very large age spread among the Pleiades very low mass objects, or else there is a background population that has a similar space motion.

Roque 1: Despite of being an M7 dwarf which nicely fits in the spectral sequence for the Pleiades cluster, we believe it is probably not a cluster member because it does not show H_α emission and has a much too high radial velocity. To our knowledge, its radial velocity is the highest ever measured in an M7 dwarf, and may indicate membership to an old galactic population. However, we do not find in the spectrum any clear indication of a low metallicity.

4.2 Spectroscopic Properties of Young Brown Dwarfs

The study of very low mass stars and brown dwarfs is complicated mainly because of the formation of many molecules and possibly dust in their atmospheres, which shape the observed spectrum. Theoretical models have tried to reproduce the spectral distribution of well-known very cool dwarfs like VB10, with not completely successful results, e.g. Allard & Hauschildt (1995). In consequence, there is not a consensus on how to derive basic parameters like effective temperature, gravity and metallicity. From the study of low-luminosity objects in clusters of known age, distance and metallicity, we hope to learn something about the structure and evolution of their atmospheres. In this work we can compare the spectra of the Pleiades very low mass objects with some of the very late-type field dwarfs.

In the previous section we have concluded that one of the BD candidates is very likely a twin of Teide 1. These two objects define the cool end of the presently known spectral sequence for Pleiades members. Recent applications of the Li-test have shown that this sequence goes beyond the substellar limit. Lithium has been detected in PPl 15 (Basri et al. 1996) and Teide 1 (Rebolo et al. 1996), but not in HHJ3 and HHJ10 (Marcy,

Basri & Graham 1994; Martín et al. 1994), which have spectral types of M6 (Steele & Jameson 1995) and M5.5 (Martín et al. 1994), respectively. The lack of lithium implies that Pleiades objects earlier than $\sim$ M6.5 are probably stars. The Li detection in PPl 15, although with a depleted abundance, indicates that the transition between stars and brown dwarfs takes place at spectral types around M6.5. Pleiades members with spectral types M7 and later are very likely brown dwarfs, as confirmed by the Li detection in Teide 1.

We can learn about the atmospheres of young brown dwarfs by comparing them with field stars, and vice versa. In general the spectroscopic properties seem dominated by the effective temperature, because young brown dwarfs and M8–M9 field dwarfs, have similar overall spectral characteristics. However, a close look reveals that there are some differences:

• The Pleiades very low mass objects tend to have lower values of NaI EW than the M6–M9 standards (Figure 5a). This trend was also noted by Steele & Jameson (1995) among M2–M6.5 Pleiades stars. The NaI doublet is known to be gravity-sensitive because it is very weak in giants. Since Pleiades very low mass stars and BDs have lower gravities than main sequence stars by about a factor of only $\sim$ 2, the observed weakening of the NaI lines confirms that they are quite sensitive to small changes in gravity.

• The VO index tends to be slightly higher in the Pleiades objects than in the field dwarfs (Figure 5b), but not the A (CaH) and TiO indices. We interpret this result as follows: the CaH and TiO molecular bands have similar strengths because the standards have the same metallicity as the Pleiades, i.e. solar, but the VO-index is different because it may have some sensitivity to gravity. An alternative interpretation of the VO difference between Pleiades and field dwarfs has been suggested by the referee of this paper. It may be that the indices that we have used to compute the spectral types (PC3, PC4, PC5) carry systematic errors when applied to low gravity Pleiades objects. If that were the case, the VO-index would suggest that Teide 1 and Calar 3 are about 1 spectral subclass later, i.e. M9 instead of M8. Such a consideration warns one of the limitations of using spectral types which are originally defined for field dwarfs for another class of objects as young brown dwarfs.

• The pseudocontinuum in the range 650–750 nm is more depressed in Teide 1 and Calar 3 than in the M8 standards, thereby explaining their also higher (R–I) color (Zapatero-Osorio et al. 1996). Possible reasons for these color differences are gravity-dependent formation of dust in cool photospheres (Tsuji, Ohnaka & Aoki 1996), and/or the presence of circumstellar material. The second hypothesis would also help to explain the large spread in I-magnitudes for a given spectral type (Figure 4), without invoking a large age spread. It will be very interesting to test the presence of dust and circumstellar disks with IR photometry and spectroscopy.

4.3 Future CCD Brown Dwarf Surveys

The results obtained in this work could be used to improve future photometric searches. The success rate of the broad-band CCD survey of Zapatero-Osorio et al. (1996) is ∼25%. Other photometric surveys do not seem to have a higher success rate. For instance, Martín (1993) obtained optical spectra for five BD candidates from the (I–K) survey of Simons & Becklin (1992) and found no dwarf later than M4 among them. Hamilton & Stauffer (1993) obtained optical spectra for seven objects with I=16–17.8, and found only one with spectral type later than M6 (PPl 1).

Proper motion surveys have a better chance of success (Hambly, Hawkins & Jameson 1993; Rebolo et al. 1995), but they need images at two epochs separated by many years because the mean proper motion of the Pleiades is only 0.05 arcsec yr^{-1}. Steele & Jameson (1995) obtained low-resolution spectroscopy of 33 proper motion members with I=13.5–17.5, and classified them as dwarfs with spectral types in the range M2–M6.5 from comparison with a few reference stars.

Based on the shape of the spectra that we have analyzed in this work, we propose that CCD photometric surveys could use filters with moderately narrow passbands. Taking into account the pseudocontinuum points of the M8–M9.5 dwarfs, and trying to avoid regions of strong telluric absorption and sky airglow we have selected the following passbands: 730–758 nm, 810–838 nm and 900–928 nm. Hence, the filters that we propose are 28 nm wide only, which is a factor of ~ 8 less than standard R,I filters. There is a loss of efficiency but it is not as large as it may seem, because we have chosen spectral regions of maximum emission in the brown dwarfs. As a further compensation we may add that the use of our filters would allow one to carry out the

CCD surveys in non-dark conditions (moon background, light pollution), which are needed if using for instance the R-band. Moreover, two problems of using broad-band filters in large aperture telescopes would be alleviated; the saturation of bright stars and the high level of sky background in the near-IR.

While the (R–I) color is known to saturate for spectral types later than $\sim$ M7 (Bessell 1991), simulations (using spectra) of the colors given by our filters indicate that they increase motonically from M4 to M9.5, and thus it would be useful to discriminate between BDs and background mid-M dwarfs in young open clusters. The filters would have to be specially manufactured, but, since follow-up spectroscopy of very faint BD candidates consumes a lot of large-aperture telescope time, we believe that future photometric searches should be optimized by using narrow pseudocontinuum filters like the ones suggested by us.

Another possible way of increasing the success of photometric surveys is to combine optical, near-IR and IR filters, such as for instance standard broad-band R, I, J and K filters. The disadvantage would be that multi-band observations require more telescope time and calibration efforts.

5. CONCLUSIONS

We have obtained optical-near-IR spectroscopy of eight new photometric BD candidates in the Pleiades cluster found by Zapatero-Osorio et al. (1996). In addition we observed the Pleiades objects PPl 1, 14, 15, and Teide 1, and several well-known very late-type standards. We have used three relationships between pseudocontinuum ratios and spectral type, in order to classify the Pleiades objects. We have derived the absorption strength of molecular (CaH, TiO, VO) bands and the equivalent widths of photospheric atomic features (KI, NaI), and chromospheric H_α emission. We have also obtained radial velocities although with considerable uncertainty (typically ± 30 km s^{-1}) due to our low spectral resolution.

One of the new BD candidates, namely Calar 3, has a similar I-band magnitude and spectral type as Teide 1 (M8). It also has H_α emission and radial velocity consistent with membership in the Pleiades. Hence, this object is very likely a twin of Teide 1, i.e. a new Pleiades brown dwarf. Other interesting objects are Calar 1, 2, 5 and Roque 1.

Calar 2 and 5 might be cluster members (consistent radial velocities) but they are about 1 magnitude too faint in the I-band for their spectral types (M6, M6.5), and a rather large age spread would have to be invoked if they were members. Calar 1 is the coolest dwarf ever found towards the Pleiades (M9). However, its radial velocity is not at all consistent with membership. It is remarkable that Roque 1 has an even higher velocity. The presence of two very late dwarfs with high velocity was unexpected in the small volume surveyed by Zapatero-Osorio et al. The rest of the BD candidates have too early spectral types (M4–M6) and in some cases too high radial velocities, and we believe that they are background stars which have contaminated the photometric survey.

PPl 15 (M6.5), Teide 1 (M8) and Calar 3 (M8) define a spectral sequence at the substellar mass limit and beyond in the Pleiades cluster, according to the lithium test. Comparison of their spectra with field dwarfs indicate that in general they are very similar,but we have tentatively identified a few subtle differences: In the Pleiades BDs, the NaI doublet tends to be weaker and the VO-index stronger than in the field stars. These differences are probably due to lower gravity in the Pleiades objects, as they are young and still contracting. The difference in VO also warns us of the limitations of using the spectral type classification of field dwarfs for young brown dwarfs. We have also remarked on a difference in the pseudocontinuum in the region 650–750 nm, in the sense that the M8 Pleiades tend to have higher PC2 indices. We suggest that it could be due to gravity-sensitive dust formation, and/or circumstellar extinction.

Our results indicate that background late-type dwarfs (M4–M6) are a significant source of contamination ($\sim$50%) in deep CCD-based surveys using broad-band filters. We argue that narrow-band indices centered at pseudocontinuum points, especially redwards of 700 nm, allow one to discriminate between mid-M contaminants and very late-M dwarfs. Hence, we propose the use of special filters for improving the success rate of future CCD brown dwarf searches in young open clusters.

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Figure Captions:

Figure 1. Final spectra of Pleiades and field very cool dwarfs observed at the WHT with ISIS (FWHM=5.8 Å). They are ordered by increasingly late spectral type from top to bottom. The strongest atomic and molecular features are marked.

Figure 2. Same as Figure 1 but for targets observed at the 3.5 m Calar Alto telescope with the TWIN spectrograph (FWHM=7.8 Å). In some spectra, bad pixels produce spurious features at 798.5 nm, and at 818.5 nm. The spectral ranges of the pseudocontinuum ratios defined in this work are joined with dotted lines. The actual integration regions are the narrow solid segments at the edges of each dotted line.

Figure 3. The PC2 and PC3 spectral index values measured in the field dwarfs (filled hexagons) and in the Pleiades objects (open hexagons). Note the different behaviour: the PC2 index peaks at around M8 and decreases for later subclasses, whereas the PC3 index increases monotonically from M5 to M9.5.

Figure 4. I-band apparent magnitudes versus spectral type subclass. Filled pentagons are used for Pleiades proper motion members from Hambly et al. (1993) with spectral types $\geq$ M4 derived by Martín et al. (1994) and Steele & Jameson (1995). Filled hexagons denote the PPl objects from Stauffer et al. (1994a,b) and Teide 1 (Rebolo et al. 1995), with spectral types derived in this work. Empty squares denote the BD candidates found by Zapatero-Osorio et al. (1996). The names of all objects with spectral type later than M5.5 are indicated. In the upper right corner, the dotted horizontal line represents the typical uncertainty in spectral type and the dotted vertical line the range in I magnitudes induced by a hypothetical age spread of 60 Myr. For this estimate we used a central age of 100 Myr for the Pleiades and the grid of models provided by F. D'Antona. The dashed line joins the I-band magnitudes of main sequence stars at the distance of the Pleiades, and hence separates the region of plausible cluster members (upper part) from that of likely background objects (lower part).

Figure 5. The NaI equivalent widths (upper panel) and VO-index values (lower panel) measured in the standards (filled hexagons) and in the Pleiades members PPl 14, PPl 15, Teide 1 and Calar 3 (open hexagons) plotted against spectral type.